

# RECENT ELECTROWEAK RESULTS FROM THE TEVATRON

**M. Bauce**

ON BEHALF OF THE CDF AND D0 COLLABORATIONS

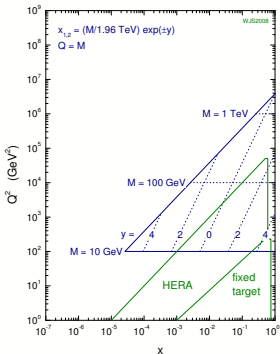
SAPIENZA UNIVERSITÀ DI ROMA

Rencontres de Moriond, EW Interactions and Unified Theories,  
La Thuile, March 14-21, 2015

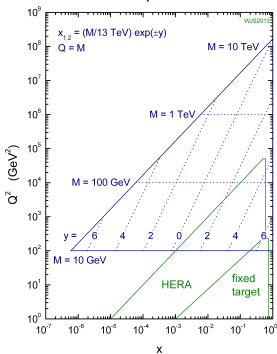


## Electroweak measurements still fundamental at the Tevatron

Tevatron parton kinematics



13 TeV LHC parton kinematics



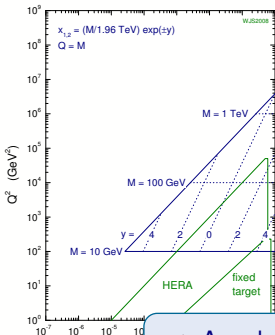
- Different parton densities with respect to LHC
- Information on PDF, narrow  $x$  range (for  $Q^2 \approx M_V^2$ ) to explore:  
 $0.002 < x < 1, \quad x = \frac{M}{\sqrt{s}} e^{\pm y}$
- Complementary to central-forward jet measurements at the Tevatron
- Help modeling MC simulations

► Thanks to the full Tevatron dataset, resulting from many years of data-taking, we have greatly improved the accuracy of EWK measurements.

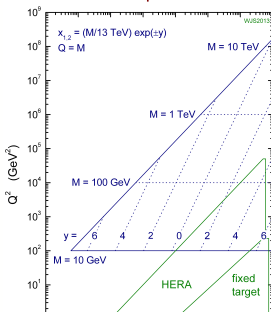


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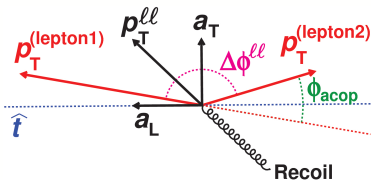


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 $0.002 < x < 1$ ,  $x = \frac{M}{\sqrt{s}} e^{\pm y}$
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- Angular distribution  $\phi^*$  in  $Z \rightarrow \mu\mu$  events
- $e$  charge asymmetry in  $W^\pm \rightarrow e^\pm \nu$  events
- Indirect  $\sin^2 \theta_W$  measurement in  $Z \rightarrow ee$  events
- $WW$ + jets production
- $WW/WZ \rightarrow \ell\nu$ + heavy flavor jets

► Thanks to  
have greatly

data-taking, we



$$\phi^* = \tan(\phi_{acop}/2) \cdot \sin \theta^*$$

$$\phi_{acop} = \pi - \phi(\ell\ell)$$

$$\cos \theta^* = \tanh((\eta_- - \eta_+)/2)$$

- $\phi^*$  is equivalent to  $p_T(\ell\ell)$ :  $\phi^* \propto a_T/M_{\ell\ell}$
- Less sensitive to detector resolution and efficiency:  $<1\%$  resolution on mrad angles
  - few % resolution uncertainty on  $p, E$

Provides information about boson momentum spectrum  $\Rightarrow$  improve MC generators (ResBos) for predictions at higher collision energy (i.e. LHC)

- Explored di-muon events in the full D0 dataset,  $\int \mathcal{L} = 10.4 \text{ fb}^{-1}$ , with  $30 \leq M_{\mu\mu} \leq 500 \text{ GeV}$
- Separate analysis for on-peak and off-peak events
- Comparison to ResBos and NNLL+NLO calculations (Banfi et al.)

ResBos arXiv:1309.1393

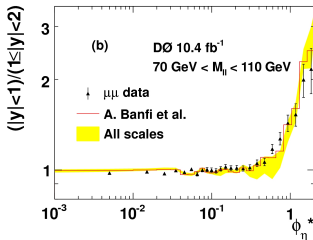
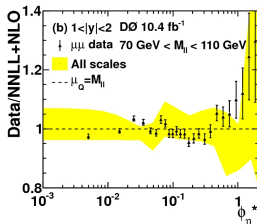
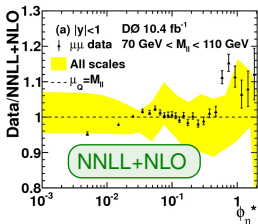
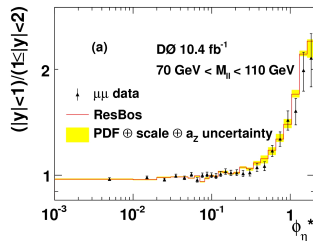
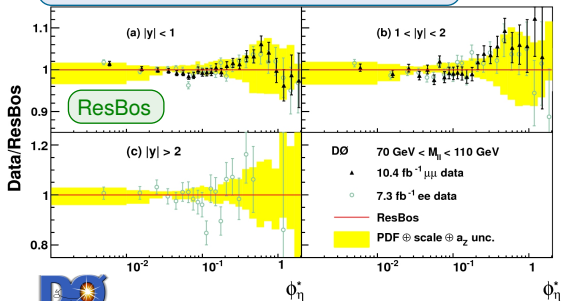
Banfi et al. JHEP01 (2012) 011



# $\phi^*$ DISTRIBUTION IN $Z \rightarrow \mu\mu$ - ON PEAK



Exp. uncert. smaller than theoretical ones



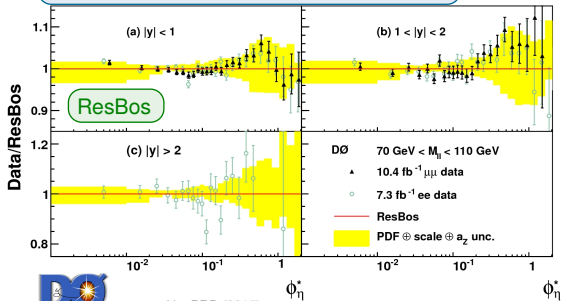
High- $\phi^*$  discrepancy observed also in  $Z \rightarrow e^+e^-$  which has different corrections



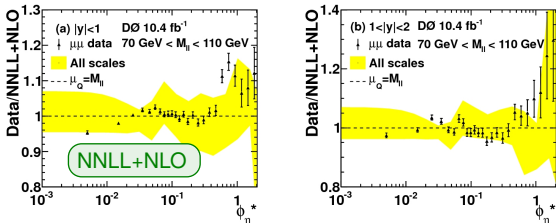
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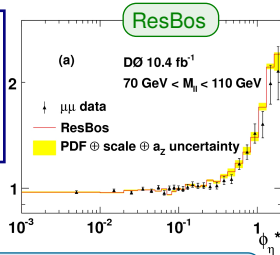
Exp. uncert. smaller than theoretical ones



accepted by PRD (2015)

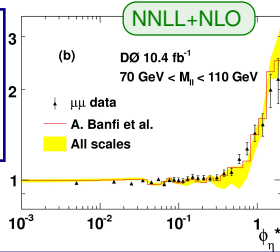


$(|y| < 1) / (1 < |y| < 2)$



Central/Forward ratio reduces theoretical uncertainties

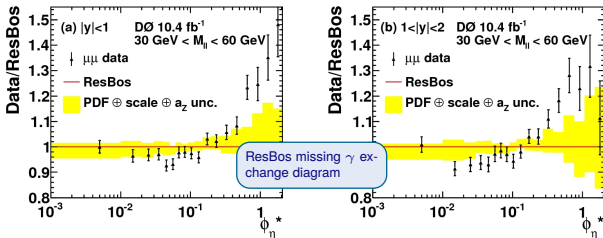
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High- $\phi^*$  discrepancy observed also in  $Z \rightarrow e^+e^-$  which has different corrections



# $\phi^*$ DISTRIBUTION IN $Z \rightarrow \mu\mu$ - OFF PEAK

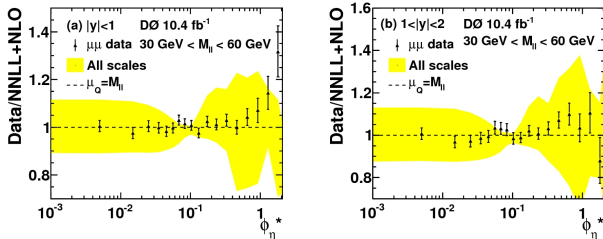


## First low-mass measurement

- More sensitive to small- $x$  effects
- Better statistics than forward rapidity region

## Also first high-mass measurement

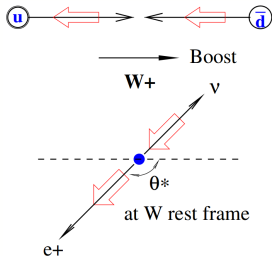
- Helpful to constrain QCD ISR for processes with high mass final state
- Low statistics, detailed comparison unavailable



accepted by PRD (2015)



# $W^{\pm} \rightarrow e^{\pm} \nu$ CHARGE ASYMMETRY

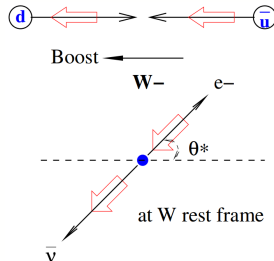


In  $p\bar{p}$  collider:

$$A(y_W) = \frac{\frac{d\sigma^+}{dy_W} - \frac{d\sigma^-}{dy_W}}{\frac{d\sigma^+}{dy_W} + \frac{d\sigma^-}{dy_W}}$$

$$= \frac{u(x_p)\bar{d}(x_{\bar{p}}) - d(x_p)\bar{u}(x_{\bar{p}})}{u(x_p)\bar{d}(x_{\bar{p}}) + d(x_p)\bar{u}(x_{\bar{p}})}$$

$\Rightarrow$  sensitive to  $u$  and  $d$  PDFs.

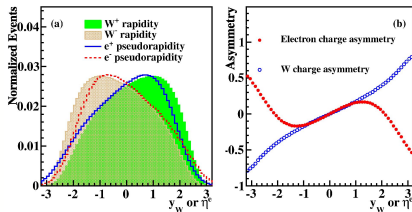


Measure  $\ell$  charge asymmetry:

- Straightforward observable, easier to determine
- Convolution of  $W$  production asymmetry and V-A decay
- $W$  asymmetry more challenging because of missing  $\nu$



PRL 112 151803 (2014)



$W$  rapidity  $\Rightarrow e$  pseudorapidity



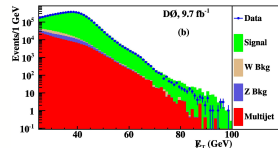
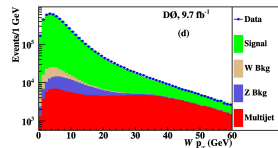
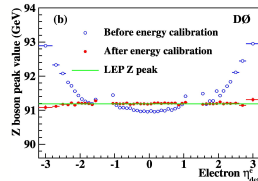
# $W^\pm \rightarrow e^\pm \nu$ CHARGE ASYMMETRY



- $W^\pm \rightarrow e^\pm \nu$  selected from the full D0 dataset
- Subtract background: multijet,  $Z \rightarrow ee$ ,  $W \rightarrow \tau \nu$ ,  $Z \rightarrow \tau \tau$
- Correct for detector effect, unfold distributions
- Compare corrected asymmetries with theoretical predictions
- Different analysis bins:

$E_T^e > 25 \text{ GeV}$	$\cancel{E}_T > 25 \text{ GeV}$
$25 < E_T^e < 35 \text{ GeV}$	$25 < \cancel{E}_T < 35 \text{ GeV}$
$E_T^e > 35 \text{ GeV}$	$\cancel{E}_T > 35 \text{ GeV}$
$25 < E_T^e < 35 \text{ GeV}$	$\cancel{E}_T > 25 \text{ GeV}$
$E_T^e > 35 \text{ GeV}$	$\cancel{E}_T > 35 \text{ GeV}$

- Residual Data/MC discrepancies covered by systematic uncertainties





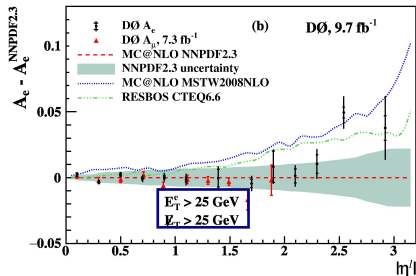
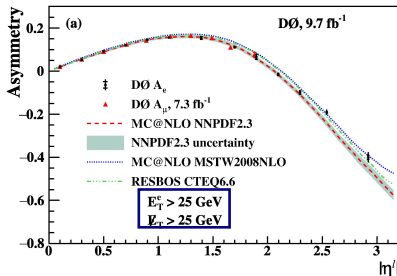
# $W^\pm \rightarrow e^\pm \nu$ CHARGE ASYMMETRY



Assuming CP, asymmetries folded in  $|\eta|$  after checking consistency



PRD 91, 032007 (2015)



Consistent with MC@NLO and NNPDF2.3

- $W$  and  $e$  charge asymmetries measured using the full D0 dataset,  $\eta$  up to 3.2
- Most precise measurement of lepton charge asymmetry to date
- First measurement of  $W$  charge asymmetry from D0 and most precise to date
- Improvement of PDF knowledge in  $Q^2$ - $x$  region of  $W$  production will have strong impact on  $m_W$  measurement:
  - ▶ expected PDF uncertainty reduction by  $\sim 30\%$



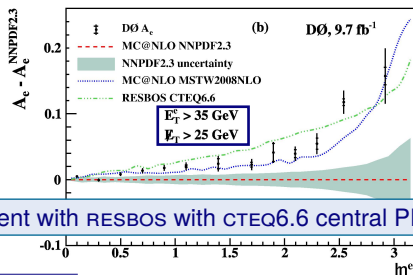
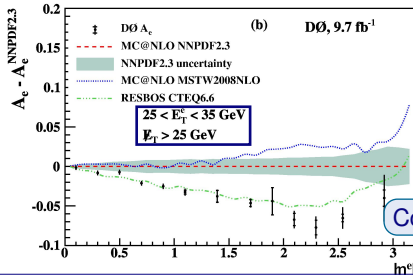
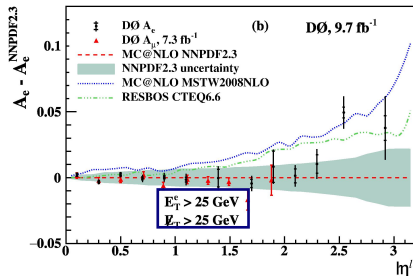
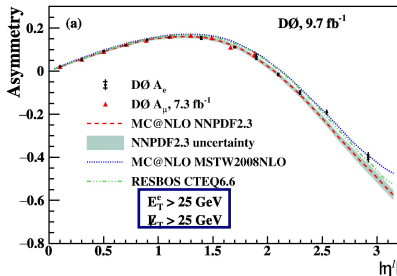
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PRD 91, 032007 (2015)



Consistent with RESBOS with CTEQ6.6 central PDF



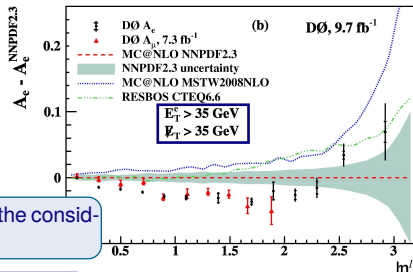
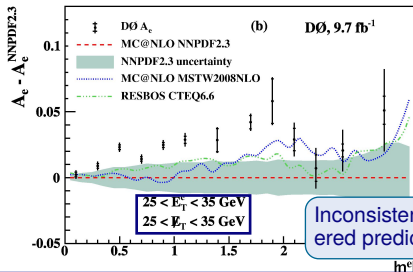
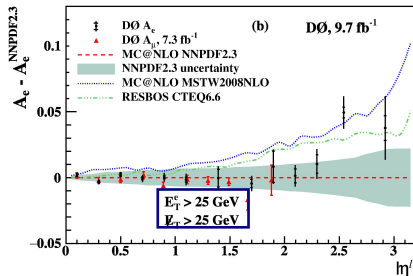
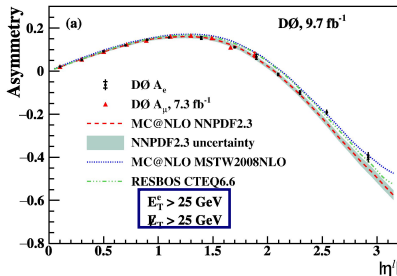
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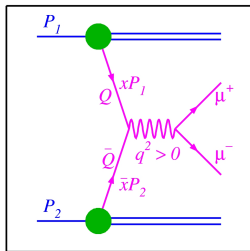


PRD 91, 032007 (2015)



Inconsistent with the considered predictions

$$p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$$



Drell-Yan dilepton production affected by the axial-vector contributions by:

$$\mathcal{L} = -i \frac{g}{\cos \theta_W} \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma_5) f Z_\mu$$

where  $g_V^f = I_3^f - 2Q_f \cdot \sin^2 \theta_W$ ,  $g_A^f = I_3^f$

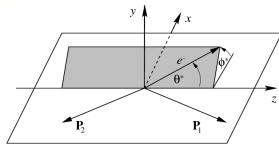
- $I_3$  and  $\sin^2 \theta_W$  couplings are modified by weak radiative corrections (few %)
- *effective* value of  $\sin \theta_W$ :

$$\sin^2 \theta_W = 1 - M_W^2/M_Z^2 \quad \rightarrow \quad \sin^2 \theta_{\text{eff}}^f = \frac{1}{4|Q_f|} \left( -\frac{g_V^f}{g_A^f} \right)$$

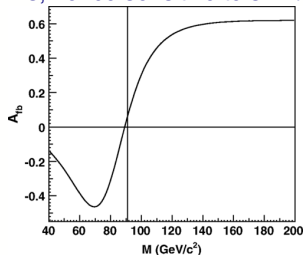
- The effective weak mixing angle ( $\theta_{\text{eff}}$ ) can be measured from the **forward-backward charge asymmetry** in the distribution of the lepton emission angle ( $A_{\text{fb}}$ )

- Reconstruct a  $\ell^+\ell^-$  pair, consider the angular distribution in the Collin-Soper rest frame
- Consider  $\theta^*$ , the polar emission angle of the  $\ell^-$  with respect to the direction of the incoming quark

$$A_{fb} \equiv \frac{\sigma(\cos \theta^* > 0) - \sigma(\cos \theta^* < 0)}{\sigma(\cos \theta^* > 0) + \sigma(\cos \theta^* < 0)} = \frac{N_F - N_B}{N_F + N_B}$$



The asymmetry is due to the interference between the vector and axial vector coupling terms, hence sensitive to  $\sin^2 \theta_{\text{eff}}$



- Measure  $A_{FB}$  in bins of  $M_{\ell\ell}$
- Produce MC simulated templates of  $A_{FB}(M_{\ell\ell}, \sin^2 \theta_W)$
- Apply corrections to data and simulation
- Compare  $A_{FB}(M_{\ell\ell})$  obtained in data to simulated templates with different  $\sin^2 \theta_W$  values ( $\chi^2$  fit)

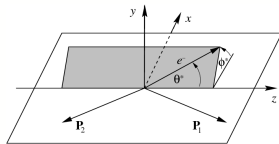


## $A_{fb}$ : ANALYSIS STRATEGY

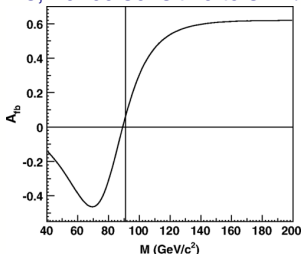


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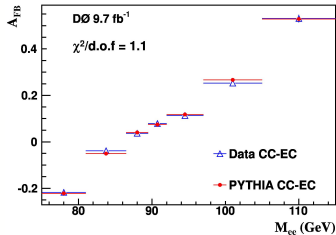
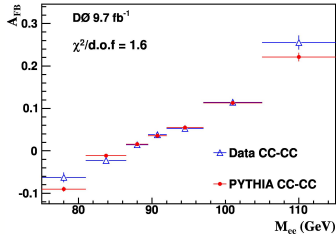
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Improved  $e$  reconstruction and calibration, extended to the full collected dataset, extended the  $\eta$  region coverage! (wrt to previous version of the analysis)





# $\sin^2 \theta_W$ MEASUREMENT



	CC-CC	CC-EC	EC-EC	Combined
$\sin^2 \theta_W$	0.23140	0.23142	0.22986	0.23138
Statistical	0.00116	0.00047	0.00276	0.00043
Systematic	0.00009	0.00009	0.00019	0.00008
Energy Calibration	0.00003	0.00001	0.00004	0.00001
Energy Smearing	0.00001	0.00002	0.00013	0.00002
Background	0.00002	0.00001	0.00002	0.00001
Charge Misidentification	0.00002	0.00004	0.00012	0.00003
Electron Identification	0.00008	0.00008	0.00005	0.00007
Total	0.00116	0.00048	0.00277	0.00044

$$\sin^2 \theta_W = 0.23139 \pm 0.00043(\text{stat.})$$

$$\pm 0.00008(\text{syst.}) \pm 0.00017(\text{PDF})$$

which translates in SM on-shell renormalization scheme and modified ResBos NLO corrections

$$\sin^2 \theta_{\text{eff}}^\ell = \mathbf{0.23147 \pm 0.00047}$$

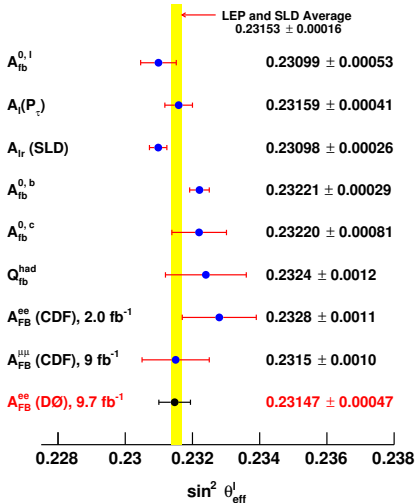




# $\sin^2 \theta_W$ MEASUREMENT



## World's best from Hadron Collider and light quark interactions



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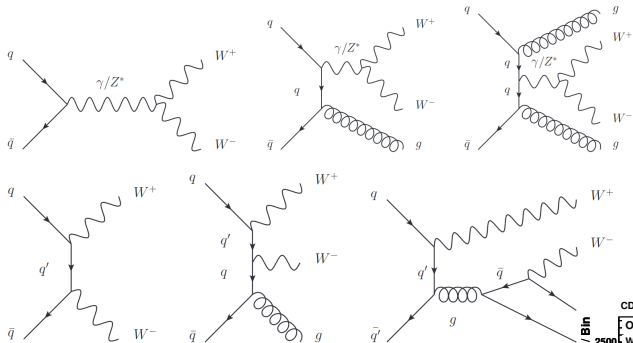
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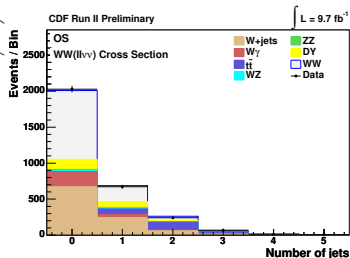


Many diagrams involved in  $WW$  production at the Tevatron:



- associated jets depending on the production mechanism
- basic to study Vector Boson Scattering
- fundamental background on the search for  $H \rightarrow W^+ W^-$

- $WW$  cross section precisely measured using 35% of the dataset:  
 ► Extended the analysis to jet-associated production

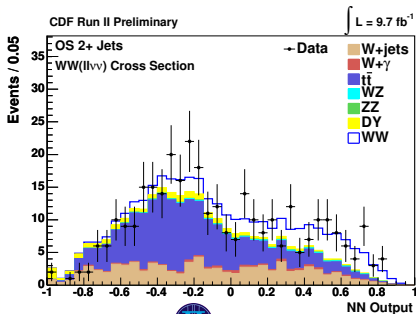
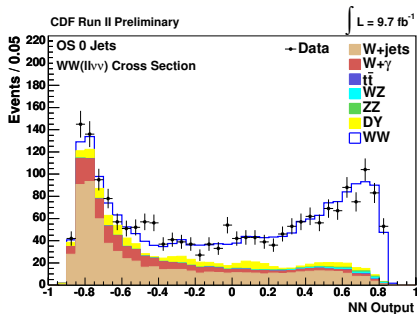




# WW+JETS



- Events with a  $\ell^+\ell^-$  pair ( $\ell=e,\mu$ ), significant  $\cancel{E}_T$
  - Different analysis *bins*, depending on the jet multiplicity
- $$\cancel{E}_{T,rel} \equiv \begin{cases} \cancel{E}_T & \text{if } \Delta\phi(\vec{\cancel{E}}_T, \text{lepton}, \text{jet}) > \frac{\pi}{2} \\ \cancel{E}_T \sin(\Delta\phi(\vec{\cancel{E}}_T, \text{lepton}, \text{jet})) & \text{if } \Delta\phi(\vec{\cancel{E}}_T, \text{lepton}, \text{jet}) < \frac{\pi}{2} \end{cases}$$
- |        |                                  |                |
|--------|----------------------------------|----------------|
|        | 1 jet: $15 \leq E_T \leq 25$ GeV |                |
| 0 jets | 1 jet: $25 \leq E_T \leq 45$ GeV | 2 or more jets |
|        | 1 jet: $45 \leq E_T$ GeV         |                |
- Train different NeuroBayes neural network in 0,1,2+ jets subchannels
  - Check background processes modeling in orthogonal control samples
  - Extract the cross section using a binned maximum likelihood fit to the NN output distribution, including syst. uncertainties





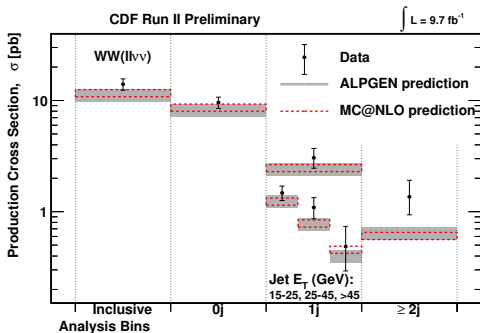
WW( $l\nu\nu$ ) Cross Section		CDF Run II Preliminary			$\int L = 9.7 \text{ fb}^{-1}$	
Jet Bin	$\sigma(\text{pb})$ Measured	Uncertainty(pb)			$\sigma(\text{pb})$	
		Stat.	Syst.	Lumi.	Alpgen	MC@NLO
Inclusive	14.0	$\pm 0.6$	$+1.6$ $-1.3$	$\pm 0.8$	$11.3 \pm 1.4$	$11.7 \pm 0.9$
0 Jets	9.6	$\pm 0.4$	$+1.1$ $-0.9$	$\pm 0.6$	$8.2 \pm 1.0$	$8.6 \pm 0.6$
1 Jet Inclusive	3.05	$\pm 0.46$	$+0.48$ $-0.32$	$\pm 0.18$	$2.43 \pm 0.31$	$2.47 \pm 0.18$
1 jet, $15 < E_T < 25 \text{ GeV}$	1.47	$\pm 0.17$	$+0.15$ $-0.11$	$\pm 0.09$	$1.26 \pm 0.16$	$1.18 \pm 0.09$
1 jet, $25 < E_T < 45 \text{ GeV}$	1.09	$\pm 0.18$	$+0.17$ $-0.12$	$\pm 0.06$	$0.77 \pm 0.10$	$0.79 \pm 0.06$
1 jet, $E_T > 45 \text{ GeV}$	0.49	$\pm 0.15$	$+0.20$ $-0.11$	$\pm 0.03$	$0.40 \pm 0.05$	$0.46 \pm 0.03$
2 or More jets	1.36	$\pm 0.30$	$+0.46$ $-0.29$	$\pm 0.08$	$0.64 \pm 0.08$	$0.61 \pm 0.05$

Unfolded result:

- jet-bin migration,
- acceptance differences,
- correction to hadronic level

Higher but consistent with theoretical predictions (ALPGEN, MC@NLO)

► First differential cross section measurement in a massive diboson state



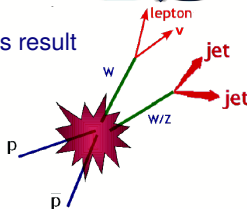


# WW/WZ+HEAVY FLAVOR JETS



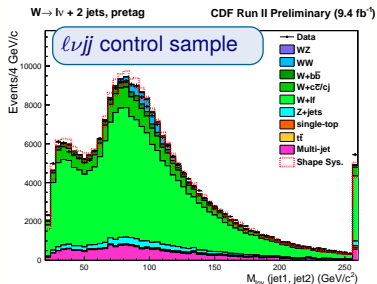
Exploit the full CDF dataset ( $\int \mathcal{L} = 9.4 \text{ fb}^{-1}$ ) and improve previous result

- Reconstruct one  $\ell (=e, \mu)$  ( $p_T(\ell) \geq 20 \text{ GeV}$ ),  $E_T \geq 15 \text{ GeV}$  (due to  $\nu$ )
- 2 jets ( $E_T \geq 20 \text{ GeV}$ ): displaced vertex for one or both (1,2 tags)
- QCD modeled from data, rejected using Support Vector Machine



NIM A 772 (2013)

Interesting validation of the  $WH \rightarrow \ell\nu + b\bar{b}$  sensitivity



Aim to separate and measure  $WW$  and  $WZ$  thanks to the different heavy flavor decay pattern of the  $W$  and  $Z$  bosons ( $W^+ \rightarrow c\bar{s}$ ,  $Z \rightarrow b\bar{b}, c\bar{c}$ ) and the analysis of the secondary-decay vertex properties

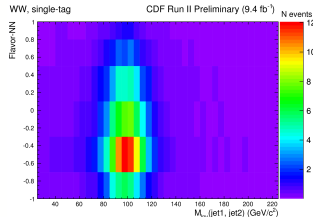
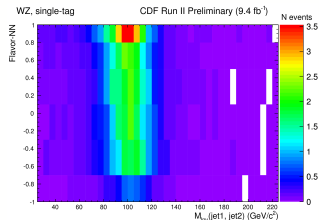
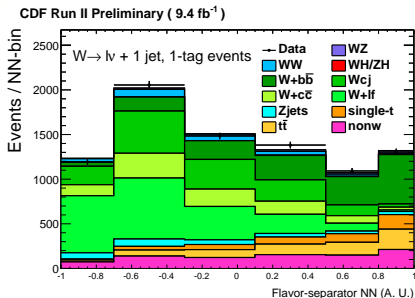




## $WW/WZ$ + HEAVY FLAVOR JETS



- ▶ Channel with 2 jets, both *tagged* as h.f. is dominated by  $WZ$  and  $W + b\bar{b}$  background
- ▶ Use a NN-based flavor discriminator for events with only one *HF-tag*
  - Separate  $b$ -quarks from  $c$ -quarks and light-flavor
  - Help discriminating  $W + c(c)$  from  $W + b\bar{b}$  as well as  $WW$  from  $WZ$





# WW/WZ+HEAVY FLAVOR JETS

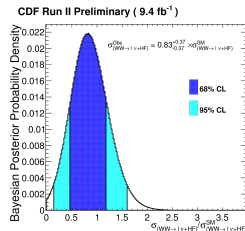
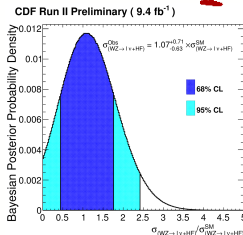
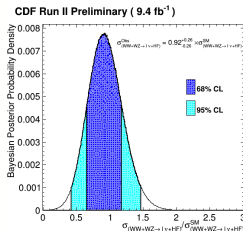
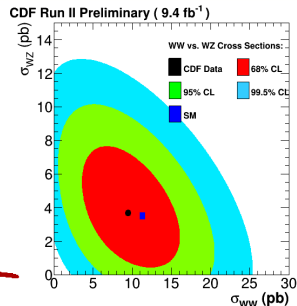


Simultaneous WW and WZ cross section measurement:

$$\sigma_{WW}^{\text{Obs}} = 9.4 \pm 4.2 \text{ pb} \quad \sigma_{WZ}^{\text{Obs}} = 3.7^{+2.5}_{-2.2} \text{ pb}$$

Total diboson cross section in  $\ell\nu jj$  final state:

$$\sigma_{WW+WZ}^{\text{Obs}} = 13.9 \pm 3.8 \text{ pb}$$





- CDF and D0 are still producing unique measurements in the Electroweak sector:
  - High precision observable measurements,  $\phi^*$ , first in off-peak region
  - Highest precision  $W$  and  $\ell$  charge asymmetry measurement, extended up to  $\eta \sim 3.2$ , comparison with several PDF models
  - World best  $\theta_W^{eff}$  measurement from hadron collider and light quark interactions
  - First  $WW$ +jets differential cross section measurement
  - Simultaneous measurement of  $WW$  and  $WZ$  in final states involving heavy flavor jets
- Combinations of CDF and D0 results are ongoing, still some results are expected in the upcoming months!



*Thanks!*

BACKUP